

SOIL TEMPERATURE REGULATES NITROGEN LOSS FROM LYSIMETERS FOLLOWING FALL AND WINTER MANURE APPLICATION

M. R. Williams, G. W. Feyereisen, D. B. Beegle, R. D. Shannon

ABSTRACT. *Many producers practice fall and winter manure spreading for economic and practical reasons. In order to minimize the risk of nitrogen (N) loss between application and crop uptake in the spring, university extension publications and industry professionals often make recommendations based on soil temperature. The objective of this research, therefore, was to determine how soil temperature affects N losses in runoff and leachate, and assess overwinter N losses based on application date and soil temperature. Phosphorus losses are discussed in a separate article. Dairy manure was surface-applied to a channery silt loam soil contained in lysimeters at soil temperatures of 15.7°C, 4.8°C, and -1.1°C, which corresponded to early fall (Oct. 22), late fall (Nov. 17), and winter (Dec. 15) applications, respectively. Nitrogen losses were determined during a series of rainfall simulations and natural precipitation events from October 2009 through March 2010. The soil temperature between manure application and the first rainfall-runoff event three days after application was held constant and significantly influenced N loss. As the soil temperature decreased, losses of $\text{NH}_4\text{-N}$, organic N, and total N exponentially increased. The form of N losses was also significantly impacted by application date and overwinter soil temperature. Early fall application of manure resulted in significant overwinter $\text{NO}_3\text{-N}$ losses, while the winter-applied manure had significantly more overwinter $\text{NH}_4\text{-N}$ losses. Results of this research show that there are trade-off risks associated with manure application in the fall and winter and that these trade-offs need to be considered in manure management planning in order to enhance N retention and help reduce the risk of overwinter N losses.*

Keywords. *Fall-applied manure, Leachate, Lysimeter, Nitrogen, Runoff, Soil temperature.*

Soil temperature is one of the most critical factors that influences important physical, chemical, and biological processes in soil and plant science (Jury and Horton, 2004). Soil hydraulic properties are affected by soil temperature (Zuzel and Pikul, 1987; Bachmann et al., 2002). Bacterial growth and plant production are both strongly temperature dependent, as are organic matter decomposition and mineralization (Skogland et al., 1988; Cookson et al., 2002; Clark et al., 2009). Many of these processes reach maximum levels at a particular range of temperatures and decrease both above and below that

range. In northern regions of the U.S., winter is often referred to as the dormant season based on the belief that biological activity ceases during this period; however, denitrification (Bremner and Zantua, 1975; Dorland and Beau-Beauchamp, 1991; Chantigny et al., 2002) and nitrification (Malhi and Nyborg, 1979; Malhi and McGill, 1982; Cookson et al., 2002) have been reported in agricultural soils at sub-freezing temperatures. Although microbial activity has been shown to occur in frozen soils, little is known about the fate of fall- and winter-applied animal manure nitrogen (N) in areas with prolonged winter periods.

Many producers practice fall and winter manure spreading for economic and practical reasons. The primary rationale for applying manure in the fall is that there is more time available for manure spreading (Fleming and Fraser, 2000). Fewer in-field activities occur during the fall and winter than during the spring growing season. The soil is typically drier in the fall compared to the spring, which also results in less soil compaction when applying manure in the fall. Conversely, compared to spring applications, fall application of manure increases the potential that some portion of the N will be lost prior to crop uptake. In some instances, significant overwinter N losses have been reported (Bole and Gould, 1986; Nyborg and Malhi, 1986; Nyborg et al., 1990). These losses come partly in the form of nitrate-nitrogen ($\text{NO}_3\text{-N}$) leaching to groundwater (Cookson et al., 2002; Gupta et al., 2004) and nitrous oxide (N_2O) emission during winter and spring thaw (Christensen

Submitted for review in July 2011 as manuscript number SW 9283; approved for publication by the Soil & Water Division of ASABE in May 2012.

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and Tiedje, 1990). Several other studies have also shown significant losses of N in surface runoff from field plots following fall-application of manure (Converse et al., 1976; Young and Mutchler, 1976).

In order to minimize the risk of N loss between application in the fall and crop uptake in the spring, university extension publications and industry professionals often recommend applications when daily soil temperatures are cooler, typically below 10°C (Snyder et al., 2000). These recommendations, however, are often based on personal experience or laboratory incubation studies, which measure only potential N losses, rather than in-field measurements (Malhi and Nyborg, 1979; Malhi and McGill, 1982; Nyborg and Malhi, 1986; Nyborg et al., 1990; Cookson et al., 2002). The objective of this research, therefore, was to (1) determine how soil temperature affects N losses in surface runoff and subsurface leachate and (2) assess the form and magnitude of overwinter N losses based on manure application date and soil temperature. Specifically, we wanted to examine differences in N loss from manure applied both above and below the 10°C recommendation as well as manure applied on frozen soil.

MATERIALS AND METHODS

LYSIMETER COLLECTION AND DESIGN

The soil thermal cycling system used in this study followed the design described in detail by Williams et al. (2010, 2011) (fig. 1). Briefly, twenty-four undisturbed soil cores from Klingerstown, Pennsylvania (40° 39' 39" N, 76° 41' 37" W) were collected in September 2009. The soil at the site was Leck Kill channery silt loam (fine-loamy, mixed, semiactive, mesic Typic Hapludult), and the surface was covered with corn residue at the time of collection.

Each core was collected by driving a 15 cm diameter × 50 cm long schedule 80 PVC pipe into the soil between two rows of corn stubble with a 1.1 Mg drop hammer. A schedule 40 PVC end cap was placed on the bottom of each lysimeter and contained a tapped 1.25 cm diameter hole to

which a leachate collection system was attached.

In order to suppress sidewall bypass flow during subsequent rainfall simulations, the lysimeters were built after the design of Feyereisen and Folmar (2009). PVC spacers, cut from SDR 35 pipe (0.5 cm thick), were designed to provide a gap between the soil core and the lysimeter wall. The spacers were in place during insertion of the lysimeter into the soil and subsequently removed. The resultant space was backfilled with liquefied petroleum jelly, which created a watertight seal between the soil column and the lysimeter wall. A 1.6 cm diameter hole was then drilled into the lysimeter wall at or slightly below the soil surface, and a runoff collection system was installed.

The lysimeters were randomly divided into six groups of four, and each group was placed in a pre-constructed 61 × 61 × 61 cm plywood bin (fig. 1). Each bin had a 2 cm thick perforated plywood bottom with extruded polystyrene insulation (7.5 cm thick, R-value = 15) on top of the plywood. The walls of the bin were also encased with extruded polystyrene insulation (5 cm thick, R-value = 10). A commercially available electric resistance heating cable (Orbit Radiant Heating, Perkasi, Pa.) was placed in two layers, 2.5 and 7.6 cm above the insulation on the bottom of each bin, in order to create an upward heat flux representative of heat flow under field conditions (fig. 1). Masonry sand was carefully added and packed over the heating cable and around the lysimeters until the bins were filled up to the soil surface. One lysimeter from each bin was fitted with four type-T thermocouples (Culik et al., 1982) at 5, 10, 20, and 30 cm depths below the soil surface. The thermocouples along with two thermistors and an electronic relay that controlled the heating cable were connected to a datalogger, which was programmed to maintain a set temperature at the 40 cm depth.

Each lysimeter-bin assembly was placed on a custom-built cart and pushed outside a USDA Agricultural Research Service (USDA-ARS) building on the Pennsylvania State University campus from October 2009 through March 2010. The site was level and grass-covered. A tarp canopy was erected to prevent unwanted precipitation from coming in contact with the lysimeters. The soil temperature at the 40 cm depth in each bin was adjusted weekly or biweekly from 16°C to 2°C by manually decreasing the temperature of the heating cable. The manual adjustments reflected the 30-year average soil temperature cycle at a depth of 40 cm in State College, Pennsylvania (40° 47' 29" N, 77° 51' 31" W). Water was added weekly (0.5 cm depth) in order to prevent the soil surface from drying out.

MANURE APPLICATION AND RAINFALL SIMULATIONS

The dairy manure used in this study was collected from the Pennsylvania State University Research Dairy. Feces and urine were collected and stored separately in a refrigerator no more than three days prior to application. The feces and urine were mixed at a 1.7:1 ratio one day prior to application and were analyzed for nutrient content (table 1).

The lysimeters inside each of the bins were randomly designated as either a control (C) or one of three manure application treatments: early fall (EF), late fall (LF), and

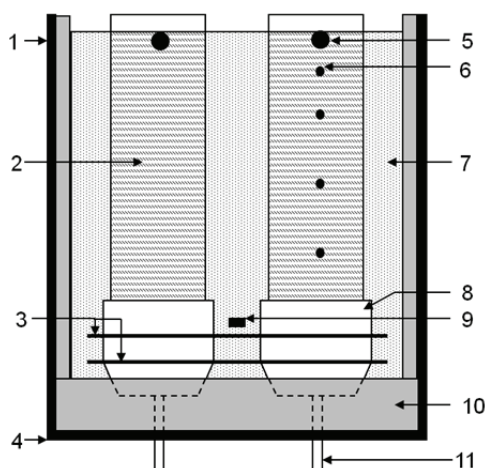


Figure 1. Cross-sectional view of soil thermal cycling system: (1) plywood bin, (2) undisturbed soil, (3) heating cable, (4) plywood bottom, (5) runoff collection, (6) thermocouple, (7) sand, (8) PVC end cap, (9) thermistor, (10) extruded polystyrene insulation, and (11) leachate collection. Only two of four soil columns are shown in the plywood bin.

Table 1. Treatment, application date, air and soil temperatures, and selected characteristics of the dairy manure.

Treatment ^[a]	Application Date	$T_{\text{air}}^{[b]}$ (°C)	$T_{\text{soil}}^{[c]}$ (°C)	Solids (%)	NH ₄ -N (kg 1000 L ⁻¹)	Organic N (kg 1000 L ⁻¹)	Total N (kg 1000 L ⁻¹)	Total P ₂ O ₅ (kg 1000 L ⁻¹)
EF	October 22	16	15.7	9.0	3.78	2.45	6.21	1.21
LF	November 17	4.5	4.8	9.9	3.73	2.37	6.11	1.16
W	December 15	-6.5	-1.1	9.1	3.18	2.77	5.93	1.13

^[a] EF = early fall, LF = late fall, and W = winter.

^[b] T_{air} = air temperature that was maintained for a four-day period (one day prior to the manure application through the rainfall simulation day) inside the temperature-controlled room/freezer.

^[c] T_{soil} = temperature of the soil at the 5 cm depth following the one-day equilibration period prior to manure application.

winter (W). On October 21, 2009, all of the lysimeter-bin assemblies were pulled inside a temperature-controlled room and the soil temperature was allowed to equilibrate to the air temperature ($T_{\text{air}} = 16^{\circ}\text{C}$) in the room for a one-day period (table 1). On October 22, manure was applied to the EF treatment at a rate of 0.39 g cm^{-2} , which was equivalent to an application rate of $38,600 \text{ L ha}^{-1}$ (table 1). The application rate was predetermined based on a manure analysis and a $225 \text{ kg total N ha}^{-1}$ recommendation; thus, 395 g total N was applied to the soil surface of each lysimeter. On October 25, three days after the manure application, each bin was individually subjected to a rainfall simulation using a modified protocol of Sharpley et al. (2001). A single nozzle (FullJet 1/2 HH SS 14WSQ, Spraying Systems Co., Wheaton, Ill.) was attached to a frame at a height of 3.05 m above the top of the bins. The simulation duration was 1 h at an average intensity of 3.8 cm h^{-1} .

Following the same procedure as the EF treatment, manure was applied to the LF and W treatments on November 17 and December 15, respectively, with all bins receiving rainfall simulations three days after each application (table 1). In order to achieve the desired air temperatures for the late fall and winter application ($T_{\text{air}} = 4.5^{\circ}\text{C}$ and -6.5°C , respectively), all of the lysimeter-bin assemblies were pushed into a large walk-in freezer (Leer ICE Merchandisers, New Lisbon, Wisc.) one day prior to manure application and maintained there until the rainfall simulation. A final, fourth rainfall simulation was conducted on January 15 ($T_{\text{air}} = -6.5^{\circ}\text{C}$). The uniformity coefficient among all ($6 \text{ bins} \times 4 \text{ simulations} = 24$) of the rainfall simulations was 0.93. The lysimeter-bin assemblies were stored under the tarp canopy for the three-week periods between the rainfall simulations, where they were subjected to ambient temperature fluctuations.

NATURAL PRECIPITATION EVENTS

Upon completion of the final rainfall simulation in January 2010, the tarp canopy covering the lysimeter-bin assemblies was removed. This exposed the lysimeters to both ambient air temperature and precipitation. From January through March 2010, a total of five events (two snowmelt, three rainfall) produced runoff, leachate, or both. Snowmelt events occurred on February 22 and March 5, 2010, and were the result of 15 cm of snow that fell on February 12. Rainfall events occurred on January 25, March 15, and March 29, 2010, with rainfall depths of 3.5, 3.6, and 1.5 cm, respectively. The soil temperature at 40 cm was held constant at 2°C until mid-March, when it was increased biweekly to reflect the warming air temperatures.

SAMPLE ANALYSIS

During both the rainfall simulations and natural precipitation events, runoff and leachate were collected. Water samples were refrigerated at 4°C immediately after collection until analysis. Ammonium-nitrogen (NH₄-N) and NO₃-N concentrations were determined colorimetrically on filtered ($0.45 \mu\text{m}$) runoff and leachate water. Total N concentration was determined colorimetrically after alkaline persulfate digestion following the method of Patton and Kryskalla (2003). Nutrient losses were then calculated by multiplying the concentration of the nutrient by the volume of the sample. Organic N losses were calculated as the difference between total N and inorganic N (NH₄-N + NO₃-N).

When the lysimeters were collected in September 2009, soil samples were taken from 0-15, 15-30, and 30-45 cm depths adjacent to the outside of the lysimeter wall. These samples were used to establish a baseline for the amount of nutrients in the soil prior to manure application. At the conclusion of the study, the manure remaining on the soil surface of the EF, LF, and W treatments was removed and soil samples were collected from within the lysimeter from 0-15, 15-30, and 30-45 cm depths within all of the lysimeters. All soil samples were air dried and sieved (2 mm). Inorganic N was extracted with 2 M KCl following the method of Mulvaney (1996) with NO₃-N and NH₄-N in extracts determined by a flow injection analyzer (Lachat Instruments, 2001, 2003). The final and initial soil samples were then compared to calculate the nutrient level change, thus determining the nutrients that would remain in the soil for potential crop use in the spring.

STATISTICAL ANALYSIS

The effect of soil temperature on hydrology was determined by calculating the percentage of total water loss (runoff + leachate) that was partitioned to runoff (or leachate). The percentages were then evaluated by ANOVA using the general linear models procedure (PROC GLM). Soil temperature effects on N loss during the first rainfall simulation after manure application for each treatment were evaluated by ANOVA using PROC GLM, with results shown as bolded values in table 2. Similarly, soil temperature effects on overwinter N loss from all rainfall simulations and natural precipitation events were evaluated by ANOVA using PROC GLM. Water quality data that were below the analytical detection limit for N (0.1 mg L^{-1}) were assigned a value that was equal to one-half of the detection limit for statistical analysis purposes (Hornung and Reed, 1990). Manure application treatment effects on soil N concentrations were evaluated by ANOVA using the mixed

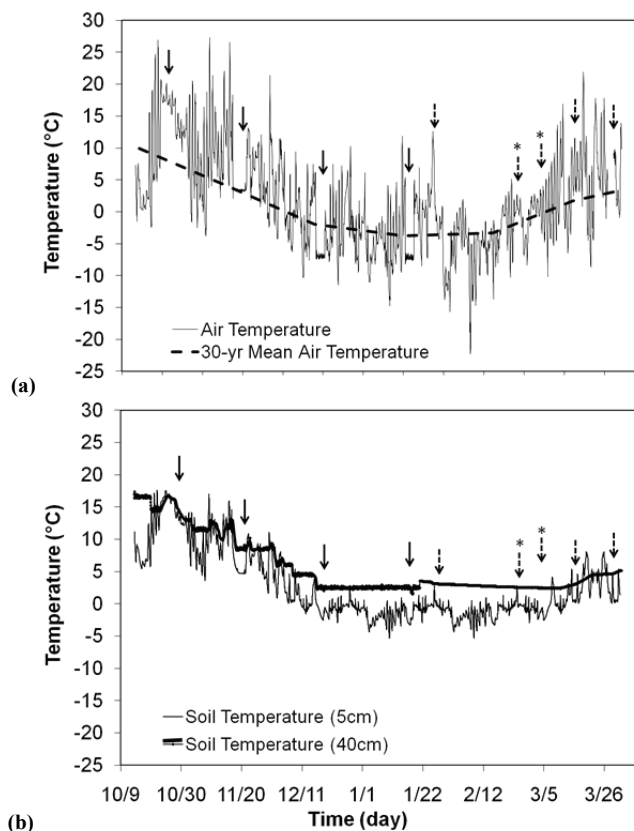


Figure 2. Mean (a) air temperature and (b) soil temperature at 5 and 40 cm depths for all treatments from October 2009 through March 2010. Solid arrows indicate rainfall simulations. Dashed arrows indicate natural precipitation events that produced runoff, leachate, or both. Asterisks above the dashed arrows indicate snowmelt.

model procedure (PROC MIXED) with manure treatment as the main effect and depth as the split-plot effect. Pairwise comparisons for all analyses were made using Tukey's Studentized range (HSD) test in order to separate treatment means. A probability level of 0.05 was used to evaluate statistical significance of treatment effects in all analyses. All statistics were completed in SAS version 9.1 (SAS, 2002).

RESULTS

AIR TEMPERATURE, SOIL TEMPERATURE, AND HYDROLOGY

The experimental system used in this study was designed to simulate a natural soil temperature profile by controlling the upper and lower boundary conditions (air temperature and soil temperature at a depth of 40 cm, respectively) of the soil core (Williams et al., 2010). In general, ambient air temperatures decreased throughout the fall and began to warm at the onset of spring (fig. 2a). Air temperatures ranged from 27°C (Oct. 23) to -21°C (Jan. 27) over this time period, and mean monthly temperatures were within one standard deviation of the 30-year temperature record (1979-2008). The manual adjustment of the heating cable was able to replicate changes in soil temperature at a depth of 40 cm that would typically occur in the field (Williams et al., 2010). However, the manual adjustment resulted in step changes rather than the gradual change observed

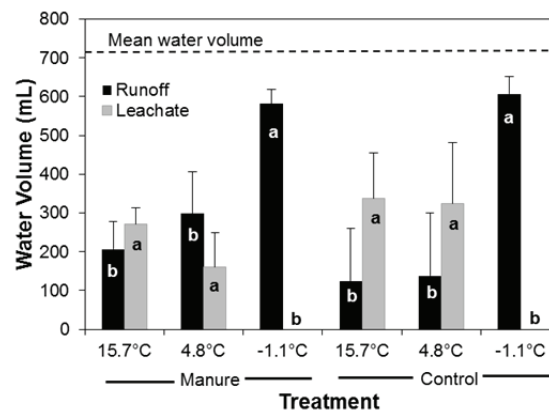


Figure 3. Runoff and leachate water volume based on soil temperature at a 5 cm depth. Error bars represent one standard deviation. Bars with the same color and letter are not statistically different at $\alpha = 0.05$.

naturally (Johnsson et al., 1995; Hu et al., 2006) (fig. 2b). Soil temperature at the 5 cm depth was approximately equal to the air temperature following the one-day equilibration period prior to the October and November rainfall simulations (table 1). Conversely, when the air temperature was maintained at -6.5°C prior to the December and January simulations, the soil temperature at the 5 cm depth reached equilibrium at -1.1°C and -0.5°C, respectively. These values correspond to the temperature of the frozen water contained in the soil pores.

Soil temperature at the 5 cm depth significantly influenced hydrology during the rainfall simulations (fig. 3). As the soil temperature decreased, the volume of runoff increased. This, in turn, resulted in decreased leachate volumes. Trends were similar for both manured and control treatments, although adding manure to the soil surface increased the volume of runoff compared to the control when the soil was not frozen (fig. 3). On average, a decrease in soil temperature from 15.7°C to 4.8°C resulted in a 12% increase in runoff volume for all treatments. This relationship, however, was not significant due to high variability among soil cores. A decrease in soil temperature from 4.8°C to -1.1°C resulted in an average increase in runoff volume of 56% for all treatments. Thus, the frozen soil (-1.1°C) resulted in 79% of the water volume becoming runoff, which was significantly more than the 23% average for non-frozen soil (15.7°C and 4.8°C).

Of the five natural events following the series of rainfall simulations, only two produced runoff. The first event occurred on January 25, in which 3.5 cm of rain fell over the course of the day on frozen soil. The second event was a snowmelt on February 22. The other three events produced exclusively leachate due to their low intensity and unfrozen soil conditions.

EFFECT OF SOIL TEMPERATURE ON NITROGEN LOSS

Soil temperature was a significant factor in determining the loss of N in both runoff and leachate (table 2). In this section, N losses will be reported in terms of the first rainfall simulation after manure application for each treatment (table 2, bolded values) in order to assess trends in N loss at different soil temperatures. Results from the other rainfall

Table 2. Mean N losses in runoff and leachate during the rainfall simulations.^[a]

	Date	Mean Runoff Loss (mg)				Mean Leachate Loss (mg)			
		C	EF	LF	W	C	EF	LF	W
NH ₄ -N	Oct. 25	BD	1.6 ab	BD	BD	BD	0.9 b	0.1 a	BD
	Nov. 20	0.1 a	0.4 a	12.0 c	0.2 a	0.2 a	0.3 a	3.6 ab	0.1 a
	Dec. 18	0.2 a	0.4 a	3.6 b	50.3 d	n/a	n/a	n/a	n/a
	Jan. 15	0.1 a	0.4 a	2.5 ab	5.9 bc	n/a	n/a	n/a	n/a
NO ₃ -N	Oct. 25	1.3 a	0.1 a	1.6 a	2.0 a	9.2 a	4.7 a	8.3 a	5.7 a
	Nov. 20	0.3 a	10.9 bc	0.4 a	0.5 a	4.1 a	21.9 b	1.1 a	3.2 a
	Dec. 18	1.5 a	14.9 c	7.4 b	1.2 a	n/a	n/a	n/a	n/a
	Jan. 15	1.6 a	14.1 c	11.1 bc	0.4 a	n/a	n/a	n/a	n/a
Total N	Oct. 25	2.1 a	8.3 b	2.3 a	2.5 a	10.1 a	10.5 a	9.2 a	5.9 a
	Nov. 20	0.4 a	11.7 b	20.5 c	0.6 a	4.2 a	22.7 b	11.2 a	3.3 a
	Dec. 18	2.7 a	17.7 c	16.3 c	87.4 d	n/a	n/a	n/a	n/a
	Jan. 15	2.9 a	17.2 c	17.7 c	15.5 c	n/a	n/a	n/a	n/a

^[a] C = control, EF = early fall, LF = late fall, and W = winter treatment. Means within the same row followed by the same letter are not significantly different at $\alpha = 0.05$. **Bold** values indicate the rainfall simulation immediately following manure application. BD denotes below detection limit, and n/a denotes that there was not any leachate collected during the rainfall simulation.

simulations as well as the natural precipitation events are presented in the subsequent section on seasonal and overwinter N losses. Runoff losses of NH₄-N for the EF treatment were not significantly greater than the control, which did not have any detectable losses (<0.1 mg). However, as the soil temperature decreased, losses of NH₄-N in runoff from the first rainfall simulation after manure application increased exponentially (table 2, bolded values). Mean NH₄-N losses of 1.6, 12.0, and 50.3 mg were observed in runoff for the EF, LF, and W treatments, respectively. Nitrate-N losses in runoff were low for all manure treatments during the first rainfall after manure application and did not differ significantly from the control treatment. Losses of 0.1, 0.4, and 1.2 mg were observed for the EF, LF, and W treatments, respectively (table 2, bolded values).

When the soil temperature was greater than 0°C, mean organic N losses in runoff increased as temperature decreased, but the trend was not significant (not shown). Organic N losses, however, were significantly higher in runoff for the W treatment. Organic N losses of 6.6, 7.4, and 39.3 mg were recorded for the EF, LF, and W treatments, respectively. Runoff losses of total N increased as soil temperature decreased, with mean values of 8.3, 20.5, and 87.4 mg observed for the EF, LF, and W treatments, respectively (table 2, bolded values).

Leachate losses of NH₄-N, NO₃-N, and total N also var-

ied among treatments. Ammonium-N leachate losses increased as the soil temperature decreased; however, this trend was not significant. Losses of 0.9 and 3.6 mg NH₄-N were observed for the EF and LF treatments, respectively (table 2, bolded values). Nitrate-N in leachate for the EF and LF treatments were less than but not significantly different from the control. The EF and LF treatments had leachate losses of 4.7 and 1.1 mg NO₃-N, respectively. For the EF and LF treatments, mean total N leachate losses were 10.5 and 11.2 mg, but were not significantly different from the control (table 2, bolded values). The W treatment did not have any leachate losses due to the frozen soil conditions at the time of the first rainfall simulation after manure application.

OVERWINTER NITROGEN LOSS

Losses of NH₄-N, NO₃-N, and total N in runoff and leachate from all rainfall simulations and natural events are shown in tables 2 and 3, respectively, on an event-by-event basis. Following the first rainfall simulation after manure application for each treatment, NH₄-N in runoff decreased significantly during the second rainfall simulation after manure application. Losses of 0.4, 3.6, and 5.9 mg of NH₄-N in runoff were observed for the EF, LF, and W treatments, respectively (table 2). During subsequent rainfall simulations and natural events that produced runoff, mean

Table 3. Mean N losses in runoff and leachate during the natural precipitation events.^[a]

	Date	Mean Runoff Loss (mg)				Mean Leachate Loss (mg)			
		C	EF	LF	W	C	EF	LF	W
NH ₄ -N	Jan. 24	BD	0.1 a	BD	5.0 b	0.3 a	0.4 a	0.3 a	1.0 b
	Feb. 22	0.1 a	0.7 a	1.0 ab	3.0 b	BD	0.2 a	0.1 a	0.1 a
	Mar. 5	n/a	n/a	n/a	n/a	0.1 a	BD	BD	0.1 a
	Mar. 15	n/a	n/a	n/a	n/a	0.1 a	0.1 a	0.1 a	BD
	Mar. 29	n/a	n/a	n/a	n/a	BD	0.1 a	BD	BD
NO ₃ -N	Jan. 24	0.2 a	6.7 b	2.1 a	BD	3.3 b	12.4 c	17.4 c	0.8 a
	Feb. 22	0.1 a	0.3 a	0.2 a	BD	0.5 a	2.7 b	4.8 b	BD
	Mar. 5	n/a	n/a	n/a	n/a	5.3 b	3.5 b	10.4 c	2.5 b
	Mar. 15	n/a	n/a	n/a	n/a	3.2 b	4.1 b	1.7 ab	1.9 ab
	Mar. 29	n/a	n/a	n/a	n/a	0.4 a	1.3 ab	3.3 b	6.9 b
Total N	Jan. 24	1.9 a	8.2 b	2.8 a	7.8 b	5.4 b	14.9 c	19.8 c	4.9 b
	Feb. 22	0.6 a	2.3 a	2.6 a	5.1 b	1.0 a	3.5 b	6.1 b	1.3 a
	Mar. 5	n/a	n/a	n/a	n/a	5.9 b	4.5 b	11.3 c	3.3 b
	Mar. 15	n/a	n/a	n/a	n/a	4.3 b	6.1 b	2.9 b	3.2 b
	Mar. 29	n/a	n/a	n/a	n/a	1.0 a	2.5 b	4.5 b	7.9 b

^[a] C = control, EF = early fall, LF = late fall, and W = winter treatment. Means within the same row followed by the same letter are not significantly different at $\alpha = 0.05$. BD denotes below detection limit, and n/a denotes that there was not any runoff collected during the event.

Table 4. Total overwinter mean N losses in runoff and leachate.

Nutrient Loss ^[a]		Treatment ^[b]			
(mg)		C	EF	LF	W
NH ₄ -N	RO	0.4 a	3.5 b	19.1 c	63.4 d
	L	0.7 a	1.9 a	4.3 a	1.3 a
	Total	1.1 a	5.4 b	23.4 c	64.7 d
NO ₃ -N	RO	4.3 a	41.9 c	22.0 b	2.7 a
	L	20.2 a	54.2 b	46.9 b	19.9 a
	Total	24.5 a	96.0 c	68.9 b	22.6 a
Inorganic N	RO	4.7 a	45.3 b	41.1 b	66.1 b
	L	21.0 a	56.1 b	51.2 b	21.2 a
	Total	25.7 a	101.4 b	92.3 b	87.3 b
Organic N	RO	4.8 a	26.2 b	27.0 b	57.9 c
	L	9.0 a	12.9 a	9.3 a	8.2 a
	Total	13.8 a	39.1 b	36.3 b	66.0 c
Total N	RO	9.5 a	71.5 b	61.1 b	124.0 c
	L	30.0 a	69.0 b	60.5 b	29.3 a
	Total	39.4 a	140.5 b	121.5 b	153.3 b

^[a] RO denotes runoff losses, and L denotes leachate losses.

^[b] C = control, EF = early fall, LF = late fall, and W = winter. Means within each row followed by the same letter are not significantly different at $\alpha = 0.05$.

NH₄-N losses in runoff generally decreased with each successive event (tables 2 and 3). Ammonium-N losses in leachate were very low for all manured treatments following the first rainfall simulation with manure (tables 2 and 3). Results were not significantly different from the control treatment except on January 24, which was the first time leachate was collected for the W treatment (table 3). Total overwinter losses of NH₄-N were significantly different among treatments, with W > LF > EF > C (table 4). Losses of 1.1, 5.4, 23.4, and 64.7 mg NH₄-N were observed for the C, EF, LF, and W treatments, respectively, with the majority of the losses occurring in runoff (table 4).

Nitrate-N losses following the first rainfall simulation after manure application followed a different pattern for each treatment. As the soil temperature decreased at the time of manure application, the largest losses of NO₃-N for each treatment were delayed later into the winter and early spring (tables 2 and 3). The EF treatment saw a dramatic spike in mean NO₃-N losses in both runoff and leachate during the second rainfall simulation after application, while a decrease was seen in the W treatment (table 2). The largest losses of NO₃-N for the EF, LF, and W treatments occurred on November 20, January 24, and March 29, respectively. Overwinter losses of NO₃-N totaled 24.5, 96.0, 68.9, and 22.6 mg for the C, EF, LF, and W treatments, respectively (table 4). Thus, overwinter NO₃-N loss were inversely related to overwinter NH₄-N losses, with the trend

EF > LF > W = C. The largest proportion of NO₃-N was lost in leachate for all treatments.

While differences were observed among manure treatments in terms of NH₄-N and NO₃-N losses, inorganic N overwinter losses were not significant. Losses of 101.4, 92.3, and 87.3 mg of inorganic N were seen in the EF, LF, and W treatments, respectively (table 4). Alternatively, differences were observed in organic N losses. For all manured treatments, the largest loss of organic N occurred during the first rainfall simulation after manure application and decreased substantially during the following rainfall simulations and natural events (tables 2 and 3). Most of the organic N was lost in runoff, with overwinter losses of organic N being the greatest for the W treatment, with W > EF = LF > C (table 4). Total N losses, however, were more similar to the trend seen for inorganic N, with manured treatments having significantly greater losses compared to the control, but no difference among manured treatments. Overwinter total N losses of 140.5, 121.5, and 153.3 mg were observed for the EF, LF, and W treatments, respectively (table 4).

EXTRACTABLE SOIL NITROGEN LEVELS

Concentrations of NH₄-N and NO₃-N in the soil collected adjacent to the lysimeter wall at the beginning of the experiment were not significantly different among treatments. NH₄-N concentrations for all treatments decreased with depth and averaged 3.2, 1.9, and 1.1 mg kg⁻¹ for the 0-15, 15-30, and 30-45 cm depths, respectively (table 5). Similarly, NO₃-N decreased with depth and averaged 25.6, 17.2, and 10.5 mg kg⁻¹ for the 0-15, 15-30, and 30-45 cm depths, respectively (table 5).

Ammonium-N concentrations in the soil at both 0-15 and 15-30 cm depths decreased for all treatments compared to the initial conditions (table 5). The change in NH₄-N concentration at the 0-15 cm depth was significantly different for the LF treatment (-15%) compared to the C and EF treatments (-46% and 49%, respectively). Conversely, NH₄-N concentration increased at the 30-45 cm depth for all treatments including the control. The EF treatment had significantly higher NH₄-N concentration at the 30-45 cm depth compared to the other treatments (2.4 vs. 1.3 mg kg⁻¹). The soil NO₃-N concentrations decreased at all depths compared to the initial conditions for the C, EF, and LF treatments, while the W treatment increased at all depths (table 5). The W treatment saw increases in NO₃-N concen-

Table 5. Extractable soil N levels prior to and after completion of the study.^[a]

Depth (cm)		NH ₄ -N (mg kg ⁻¹)				NO ₃ -N (mg kg ⁻¹)			
		C	EF	LF	W	C	EF	LF	W
0-15	Initial	3.3 a	3.3 a	2.6 a	3.4 a	30.3 a	24.5 a	26.8 a	20.7 a
	Final	1.8 a	1.7 a	2.2 a	2.4 a	5.6 a	5.7 a	7.9 a	21.4 b
	% Diff. ^[b]	-46 a	-49 a	-15 b	-29 ab	-91 a	-77 a	-71 a	3 b
15-30	Initial	1.7 a	1.8 a	1.8 a	2.1 a	26.4 a	16.6 a	13.4 a	12.3 a
	Final	1.5 a	1.8 a	1.4 a	1.2 a	4.3 a	5.5 a	7.0 a	16.7 b
	% Diff.	-12 a	0 a	-22 a	-43 b	-84 a	-67 ab	-48 b	26 c
30-45	Initial	1.1 a	1.0 a	1.0 a	1.3 a	14.5 a	10.5 a	9.6 a	7.6 a
	Final	1.2 a	2.4 b	1.3 a	1.4 a	3.5 a	4.8 a	4.0 a	9.5 a
	% Diff.	8 a	84 b	23 a	7 a	-76 a	-54 a	-58 a	20 b

^[a] C = control, EF = early fall, LF = late fall, and W = winter treatment. Means within the same row followed by the same letter are not significantly different at $\alpha = 0.05$.

^[b] % Diff. = percentage change in soil N concentrations between the initial and final sampling dates.

tration of 3%, 26%, and 20% over the study period at 0-15, 15-30, and 30-45 cm depths, respectively, whereas the other treatments decreased by an average of 80%, 40%, and 63% at the same depths (table 5).

DISCUSSION

Infiltration of water into the soil varied significantly based on the soil temperature during the precipitation event. A 56% increase in runoff volume was observed for frozen soils compared to non-frozen soils. Soils, when frozen, can turn into massive, dense, concrete-like structures that are nearly impermeable to water; thus, frozen soils have been shown to produce increases in runoff volume in several previous studies (Zuzel and Pikul, 1987; Gray et al., 2001). Zuzel et al. (1982) reported that when the soil was frozen, 87% of the precipitation became runoff on field plots in Oregon, whereas the majority of the water infiltrated when the soil temperature was above 0°C. Soil temperature also markedly influenced the infiltration of rain water at temperatures above freezing. A 12% increase in runoff volume was observed when the soil temperature decreased from 15.7°C to 4.8°C. Differences in runoff volume between temperatures were possibly due to changes in the viscosity of the water contained in the soil pores as well as the rain water. Within the range of environmental temperatures, water viscosity changes by approximately 2% per °C (Lin et al., 2003). Thus, changes in water viscosity at the different temperatures would lead to an estimated decrease in the infiltration rate of 10% to 20% between the October 25 ($T_{\text{water}} = 18^{\circ}\text{C}$) and November 20 ($T_{\text{water}} = 10^{\circ}\text{C}$) rainfall simulations.

Results from this study also showed that the presence of manure increased the amount of runoff compared to bare soil. Manure application typically improves infiltration of rain water (Gilley and Risse, 2000) and decreases runoff; therefore, this finding was unexpected. In the current study, the small surface area of the lysimeters and the uniform manure application likely influenced the volume of runoff. The uniform application of manure may have sealed the soil surface by plugging the soil pores, and the small surface area of the lysimeters may not have provided enough time for the water to infiltrate before it was collected as runoff. While the difference in runoff volume between manured and control treatments was not statistically significant, these results should be tested at larger plot and field scales.

Numerous studies have investigated the processes and mechanisms related to N loss from surface-applied manure. Few have specifically documented N losses at different soil temperatures; however, several studies have shown that nutrient loss can be significantly greater when the soil is frozen compared to non-frozen soil. Hensler et al. (1970) reported that values of up to 20% of N, 12% of phosphorus, and 14% of potassium were lost in surface runoff from manure applied to frozen soil. Similarly, Steenhuis et al. (1981) found that when infiltration was limited, about 50% of the original manurial N was lost in runoff. In these studies as well as ours, N losses during the first rainfall-runoff

event are strongly correlated to differences in runoff volumes between frozen and non-frozen soils. Since soil temperature influences the infiltration of precipitation, it also plays a significant role in determining N losses. A decrease in soil temperature of 10.9°C between the early and late fall applications resulted in an 8-fold increase in $\text{NH}_4\text{-N}$ losses in runoff. Furthermore, a 16.8°C change in soil temperature from early fall to winter increased runoff $\text{NH}_4\text{-N}$ losses by 31 times. Therefore, if the rain water infiltrates into the soil during the first precipitation event (early fall), N losses will be relatively small. If, however, the precipitation becomes runoff due to decreased soil temperature (winter), the N losses will be substantially greater.

In addition to hydrology, other factors, such as the length of time between manure application and the first rainfall-runoff event, influenced N loss during the first precipitation event after application. Several studies have shown that N loss from poultry litter and swine manure decrease with increasing time to first runoff (Sharpley, 1997; Smith et al., 2007). Additionally, N loss from manure applied on frozen soil was significantly less when the time between application and the first rainfall-runoff event was 14 days (Williams et al., 2011). Longer time periods between manure application and first rainfall-runoff event increases the potential that N will be lost through the volatilization of ammonia (NH_3) to the atmosphere. Although NH_3 volatilization was not measured in this study, research has shown that the amount of $\text{NH}_4\text{-N}$ in runoff is dependent on the amount of volatilization between spreading and the first runoff event (Steenhuis et al., 1981). Additionally, several studies have shown that there is a strong correlation between NH_3 emission rates and temperature (Li et al., 2000; Yang et al., 2003; Campbell-Nelson, 2009). When temperatures are near 0°C, the rate of NH_3 loss is generally low, while at 19°C, loss rates are high for the first 12 h, but losses are minimal after the initial period (Sommer et al., 1991). Thus, we hypothesize that manure applied in the early fall ($T_{\text{air}} = 16^{\circ}\text{C}$) lost a larger portion of N to the atmosphere through NH_3 volatilization prior to the first rainfall event, whereas little NH_3 would have been volatilized from manure applied in the winter ($T_{\text{air}} = -6.5^{\circ}\text{C}$). Results from our study provide some insight into the relative amount of NH_3 volatilization. The EF treatment had 0.9 mg of $\text{NH}_4\text{-N}$ in leachate during the rainfall simulation immediately following manure application; however, a mean loss of 3.6 mg was observed for the LF treatment. An increase in $\text{NH}_4\text{-N}$ leachate suggests that there was less volatilization of NH_3 between application and the first event for the LF treatment.

In this study, soil temperatures not only influenced N losses during the first rainfall simulation after application, but it also played a significant role in determining overwinter N losses. Following manure application, the 5 cm soil temperature for the EF, LF, and W treatments was greater than or equal to 5°C for 40, 15, and 3 days, respectively, prior to the conclusion of the study. Laboratory incubation studies with amended and unamended soils have shown that nitrification and mineralization rates significantly decrease with decreasing soil temperatures (Malhi and Nyborg, 1979; Malhi and McGill, 1982; Nyborg and Malhi,

1986; Nyborg et al., 1990; Cookson et al., 2002). Manure applied at sub-freezing temperatures would therefore have lower nitrification and mineralization of manure N, which is primarily in $\text{NH}_4\text{-N}$ form, and less loss of $\text{NO}_3\text{-N}$ compared to manure applied at warmer temperatures. Since N losses in this study were primarily in the $\text{NO}_3\text{-N}$ form after the first rainfall event, the manure applied early in the fall at warmer soil temperatures had larger losses of N during subsequent events compared to winter-applied manure. Additionally, infiltration of water (and N) was greater during the early fall compared to the winter; thus, the manure had more interaction with the soil and potential to be nitrified compared to the winter-applied manure.

While the form of overwinter N loss varied based on soil temperature and application date, total overwinter N losses were not significantly different among the manured treatments. Manure applied in the early fall had significantly greater $\text{NO}_3\text{-N}$ loss, whereas the winter-applied manure had significantly higher $\text{NH}_4\text{-N}$ loss. Despite the similarities in overwinter N losses among manure application dates, the winter-applied manure had significantly more $\text{NO}_3\text{-N}$ remaining in the soil at all depths compared to the early and late fall applications. This is consistent with the results from N loss in runoff and leachate as well as our hypothesis on the amount of NH_3 that was lost between application and the first rainfall-runoff event. It is likely that the early fall applied manure lost a substantial portion of its N as NH_3 emissions prior to the first rainfall simulation, whereas the W treatment likely lost little. Therefore, the winter-applied manure had more N available to lose (and retain in the soil) compared to the fall applications. Additionally, the greatest losses of $\text{NO}_3\text{-N}$ in leachate from the winter-applied manure occurred during the final precipitation event (March 29) of the study compared to early fall application, which had the highest losses much earlier (November 20). This suggests that the cooler soil temperatures reduced NH_3 volatilization rates as well as nitrification over the winter, which resulted in greater soil $\text{NO}_3\text{-N}$ retention.

The results of this research are in agreement with other studies that examined the influence of manure application date on N loss. Paul and Zebbarth (1997) evaluated leaching losses from fall-applied cattle slurry and determined them to average 40 kg ha^{-1} more than the no-manure treatment. Additionally, studies have shown that N loss can vary based on the season of application. Gupta et al. (2004) reported 40% higher $\text{NO}_3\text{-N}$ leaching losses from fall-applied compared to winter-applied manure. Early fall application of dairy manure was also shown to have significantly higher concentrations of $\text{NO}_3\text{-N}$ in leachate compared to late fall and spring applications (van Es et al., 2006).

Current fall and winter manure application recommendations suggest that N loss will be less when manure is applied at soil temperatures less than 10°C but greater than 0°C . In this study, we applied manure at soil temperatures of 15.7°C , 4.8°C , and -1.1°C and found that N losses in water significantly increased as soil temperatures decreased during the first rainfall event after application. If, however, N losses due to NH_3 volatilization are considered, then N loss (atmospheric and water) prior to and during the first rainfall event may be less for manure applied during the

late fall compared to early fall and winter applications. During the late fall, NH_3 volatilization would be relatively low compared to the early fall, and runoff losses would be significantly less compared to winter application of manure on frozen soil. Thus, the current recommendation is appropriate for determining N losses relative to the first event after application. Conversely, this recommendation may not be suitable for predicting overwinter losses of N, since overwinter N losses were not found to be significantly different based on soil temperature. Our results suggest that, over a range of fall and winter soil temperatures and dates of application, overwinter N losses will be similar in magnitude but different in form. When manure is applied in the early fall, higher NH_3 volatilization losses and $\text{NO}_3\text{-N}$ losses in leachate are probable compared to winter-applied manure, from which high $\text{NH}_4\text{-N}$ losses in runoff are expected if a runoff event occurs shortly after application.

The small scale of the current study limits the ability to create new or revised recommendations, and many of the results presented need to be verified at larger plot or field scales. In addition, the current study has investigated surface application of dairy manure and does not account for reduction in $\text{NH}_4\text{-N}$ losses that would occur from incorporating the manure into the soil. In general, however, manure application on frozen soil is discouraged from an environmental loss perspective due to the potential risk of $\text{NH}_4\text{-N}$ losses in runoff from rain on frozen soil or rapid snowmelt events. Additionally, when considering N loss from the first rainfall event only, manure application at cooler temperatures in the late fall will likely minimize NH_3 loss compared to early fall application and reduce the risk of runoff losses compared to winter application. In terms of total overwinter N losses, however, the results from this study show that there are trade-off risks when applying manure in the fall and winter that should be taken into account in manure management planning. This information combined with other on-farm factors, such as slope and soil type, can be used to determine application dates that will help maximize N retention and reduce overwinter N loss.

CONCLUSION

The objective of this research was to determine how soil temperature affects N loss in runoff and leachate, and assess overwinter N losses based on manure application date and soil temperatures above and below the current recommendation of 10°C , as well as on frozen soil. Decreases in soil temperature from 15.7°C to -1.1°C significantly increased the amount of runoff volume during precipitation events, which resulted in exponential increases in N loss during the first rainfall-runoff event after manure application. Our results showed that over a range of fall and winter soil temperatures and dates of surface-applied dairy manure application, total overwinter N loss in runoff and leachate were similar in magnitude but different in form. Early fall application increased the risk of $\text{NO}_3\text{-N}$ leaching losses. Winter application increased the risk of $\text{NH}_4\text{-N}$ loss in runoff. Nitrogen retention in the soil was greatest for the winter-applied manure treatment, indicating other N loss path-

ways for the fall treatments, presumably NH_3 volatilization. The current study has shown that soil temperature is an important control of N loss over the winter season at small scale; verification at larger scales is recommended. The results provide insight for extension personnel, nutrient management planners, and producers when making manure application recommendations given local physiographic and climatic factors.

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